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Geographical and environmental perspectives for the sustainable development of renewable energy in urbanizing China

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ABSTRACT

With rapid urbanization and industrialization, China has become both the largest energy consumer and CO_2 emitting country in the world. As a clean and low-carbon energy source, renewable energy is a good choice to substitute for the exhausted fossil energy. The Chinese central and local governments have made a series of policies and optimistic plans to promote a rapid development of renewable energies. China′s renewable energy development has become a key to the sustainable development of socio-economic system. Unlike most of the current studies which mainly identified the challenges regarding policies and technologies around renewable energy or performed specific analyses for a certain kind of renewable energy, this paper summarizes the spatial disparity and consistency among the major renewable energies, coal resources, energy consumption and its major influencing factors in China, and reviews the positive and negative environmental impacts of major renewable energies. Based on the geographical and environmental perspectives, this paper recommends that the Chinese government: constructs the national energy production bases according to the resource distribution; integrates different energies on the basis of their natural features and spatial consistency; adjusts the overall layout of socio-economic development consistent with renewable energies; and promotes a moderate renewable energy development to maximize the environmental benefits.

Contents

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1. Introduction

China, with more than 1.3 billion people and 1/5 of the world population, has experienced rapid urbanization and industrialization since the reform and open policy in 1978. It has a significant impact on economic growth and environmental change, making China one of the largest economies and consumers of resources in the world [1,2]. Specifically, the energy consumption in 2011 is reported to be 3.48 billion tons of standard coal equivalent (tce), 7.1% higher than in 2010 [3]. The CO_2 emissions in 2011 have reached 9 billion tons, 28% of the world total [4]. China has become both the largest energy consumer and CO_2 emitting country in the world. As China′s high-speed economic growth is still dependent on massive energy consumption [5], and per capita energy consumption and CO_2 emissions are much lower than in developed countries, i.e. per capita CO_2 emissions is 6.6 t in China and 17.2 t in USA [4], the increasing trends of energy consumption and CO_2 emissions are most likely to continue with China′s plan to accomplish its socio-economic development goals. China is facing severe energy-related challenges, such as resources depletion and great pressure to reduce CO_2 emissions [6]. To cope with these challenges is of benefit not only to China but also to the world.

It is recognized that energy that is secure, environmental friendly, and produced and used efficiently is essential for sustainable development [7]. Renewable energy (i.e. hydropower, wind power, solar energy, biomass energy, geothermal power, ocean energy, etc.) is considered to have a high potential to be cost-efficient, reliable, not damaging to the environment and designed appropriately for local conditions [8]. It has become a driving force in the effort to sustain the earth′s natural resources and to improve the users′ quality of life [9]. Therefore, a mass of studies highlighted the need for evaluation of renewable energy as alternatives for energy [10–13]. Even some scholars proposed a 100% renewable energy system for China [14]. The Chinese central and local governments have made a series of policies and optimistic plans to promote the renewable energy development. Consequently, China′s renewable energy system has made progress at an unprecedented pace with the annual consumption increasing from 166 million tce in 2005 to 286 million tce in 2010. In 2015 the annual consumption of renewable energy has been planned to reach 478 million tce [15]. All kinds of renewable energies in China will continue to develop fast (see Table 1).

With a rapid development in recent years and a broad prospect in the future, China′s renewable energy development has become a focus of world′s attention. A mass of studies have introduced the current situation in China, focusing particularly on the barriers and opportunities [16–21]. Some scholars have circumstantiated the development situation for a certain kind of renewable energies in China, such as hydropower [22,23], wind power [24–28], solar energy [29] and biomass energy [30,31]. The above studies have reached a consensus that China′s renewable energy resources are abundant and renewable energy development is the key to China′s energy security, environment protection, and CO_2 emissions reductions. The above studies also provided some valuable insights on the sustainable development of renewable energy itself, e.g. some technical, economic and environmental problems that prevent us from being optimistic about China′s renewable energy development have been fully discussed. However, prior studies mainly identified the challenges regarding policies and technologies of renewable energies, or performed specific analyses for a certain kind of renewable energy, or emphasized the disadvantages of the spatial disparity between energy supply and demand, or stressed the positive environmental impacts of renewable energy in China. Therefore, this paper summarizes the spatial distribution of major renewable

Table 1
Achievements and goals for China′s renewable energy use in the 11th and 12th five-year period [15].

Year	2005	2010	2015
Annual consumption of renewable energy (million tce)	166	286	478
Share of renewable energy in the total energy consumption (%)	7.5	8.9	> 9.5
Installed capacity of hydropower (GW)	117.39	216.06	290
Installed capacity of grid-connected wind power (GW)	1.26	31.00	100
Installed capacity of solar PV power (GW)	0.07	0.80	21
Annual consumption of solar water heaters (million m^2)	80	168	400
Installed capacity of biomass power (GW)	2.00	5.50	13
Annual consumption of biogas (billion m^3)	8	14	22
Annual consumption of biomass fuel (million tons)	1.07	2.30	15
Annual consumption of geothermal power (million tce)	2	4.60	15

energies, coal resources, energy consumption and its major influencing factors in China in Sections 2 and 3. Secondly, positive and negative environmental impacts of major renewable energies in China are both reviewed in Section 4. Thirdly, according to the spatial disparity & consistency (illustrated in Sections 2 and 3) and the positive & negative environmental impacts (mentioned in Section 4), some corresponding recommendations for China's renewable energy developments are suggested from a geographical and environmental perspective in Section 5. Finally, some important conclusions are outlined in Section 6.

2. Spatial distribution of major renewable energies and coal resources in China

In China, the major renewable energies are hydropower, wind power, solar energy, biomass energy, geothermal power and ocean energy, and coal is playing the leading role in energy structure. The major renewable energies and coal resources in China are unevenly distributed on the whole. However, there are both spatial disparity and consistency among various renewable energies and coal resources (see Fig. 1).

2.1. Hydropower

Hydropower is currently the largest renewable energy resources in China [23]. According to the national hydro resources investigation, the exploitable hydro capacity in China is 542 GW and the corresponding annual generating production is 2.47 trillion kW h, ranked first in the world [32]. The hydropower resources are mainly distributed in the west, which is the birthplace of China's major rivers. The exploitable hydro capacities in Sichuan, Tibet and Yunnan are all larger than 100 GW. They account for over 61.3% of the nation total, followed by the neighboring provinces of Hubei, Qinghai, Guizhou, Guangxi, Xinjiang, Hunan and Gansu. The least represented are those regions such as Shanghai, Beijing, Tianjin, Jiangsu, Shandong, Hainan, Anhui, Ningxia, Hebei and Liaoning, where the exploitable hydro capacities are all smaller than 2 GW (see Fig. 1a).

2.2. Wind power

China is rich with wind power resources. Based on the national resources investigation, China's wind power resources have been mapped by China Meteorological Administration Wind and Solar Energy Resources Assessment Center (see Fig. 1b). It is reported that the onshore wind power resources available for development and utilization at the altitude of 10 m are about 253 GW, at the altitude of 50 m the resources available are more than 500 GW, and offshore wind power resources in coastal areas aggregate 750 GW [33,34]. Specifically, the wind energy regions in China can be divided into five resource bands, just as shown in Fig. 1b. In Northeast China, North China, Northwest China and along the eastern coast in China, such as Heilongjiang, Jilin, Inner Mongolia, north of Hebei, north of Gansu, north of Xinjiang, Tibet and coast of Jiangsu, wind resources are the richest, with a wind power density of 200 W/m^2 above.

2.3. Solar energy

China has enormous solar energy. Based on the national resources investigation, China's solar energy resources have been mapped by China Meteorological Administration Wind and Solar Energy Resources Assessment Center (see Fig. 1c). It is reported that the annual total amount of irradiation in China is 14.7 quadrillion kW h, i.e. 2.4 trillion tce [33,34]. Specifically, the solar radiation regions in China can be divided into five resource bands, just as shown in Fig. 1c. In west of Tibet, the annual irradiation quantity is more than 9250 MJ/m^2 and the highest. In Northwest China, North China, and a part of Northeast and Southwest China, such as Qinghai, Xinjiang, Gansu, Ningxia, Shanxi, Inner Mongolia and so on, the annual irradiation quantity is more than 5000 MJ/m^2. The deficient zone lies in South China, East China, and a part of Central and Southwest China, such as Chongqing, Guizhou, Guangxi, Hunan, Hubei, Jiangxi, Fujian, Zhejiang and so on, where the annual irradiation quantity is less than 5000 MJ/m^2.

2.4. Biomass energy

Biomass is also one of the most important renewable energies in China, mainly focusing on power generation, biogas, biomass briquettes and biomass fuel, etc. According to the assessment by the Chinese Academy of Sciences, the potential quantity of all biomass byproducts energy in China is 3511 million tce [35], and the geographic distribution of biomass byproducts is unbalanced (see Fig. 1d). In terms of potential quantity of biomass distribution, biomass energy is centralized in the southwestern and northeastern provinces. Sichuan, Yunnan and Tibet account for over 33.3% of the nation total, followed by Heilongjiang, Inner Mongolia, Henan, Jilin, Hubei, Shandong and Hunan. The least represented are those regions such as Shanghai, Beijing, Tianjin, Ningxia and Hainan.

2.5. Geothermal power

China's geothermal power is widely applied in the heating system, such as bathroom, hotel, etc. However, they have not been large-scale exploited commercially for heat or power generation. According to the statistical data from World Geothermal Congress 2010, more than 3200 geothermal spots have been found in China, and the annual naturally relieved heat is more than 104 quadrillion kJ, i.e. 3.56 billion tce [34,36]. As can be seen from Fig. 1e, the best geothermal resources mainly distribute in Southwest China, such as Tibet and Yunnan, where the temperature is above 150 °C and the heat flow is above 80 MW/m^2. The better geothermal resources mainly distribute in Zhejiang, Fujian, Guangdong, Guangxi, Hainan, Jilin, Liaoning, etc., where the temperature is from 90 °C to 150 °C and the heat flow is from 60 MW/m^2 to 80 MW/m^2. In other provinces, the geothermal resources are relatively poor.

2.6. Ocean energy

China has abundant ocean energy resources, such as tidal energy, tidal current energy, wave energy, ocean thermal energy, ocean salinity energy, etc. According to the statistical data from China Renewable Energy Society, the exploitable capacities of ocean energy in China can reach more than 100 GW, and ocean energy resources mainly distribute along the coasts of Zhejiang, Guangdong, Fujian, Shandong and Liaoning [37]. However, the actual application is little due to technical and economic effects [38]. Some universities and research institutes have designed and manufactured some lab equipment, but the capacity is small and the efficiency is low. Therefore, in the Twelfth Five-Year Plan of renewable energy development in China, the ocean energy development has not been emphasized [15].

2.7. Coal resources

Coal accounts for 68.0% of the primary energy consumption in China in 2010 [39]. It is and will continue to be a major energy resource in China because of its abundant reserves and mature

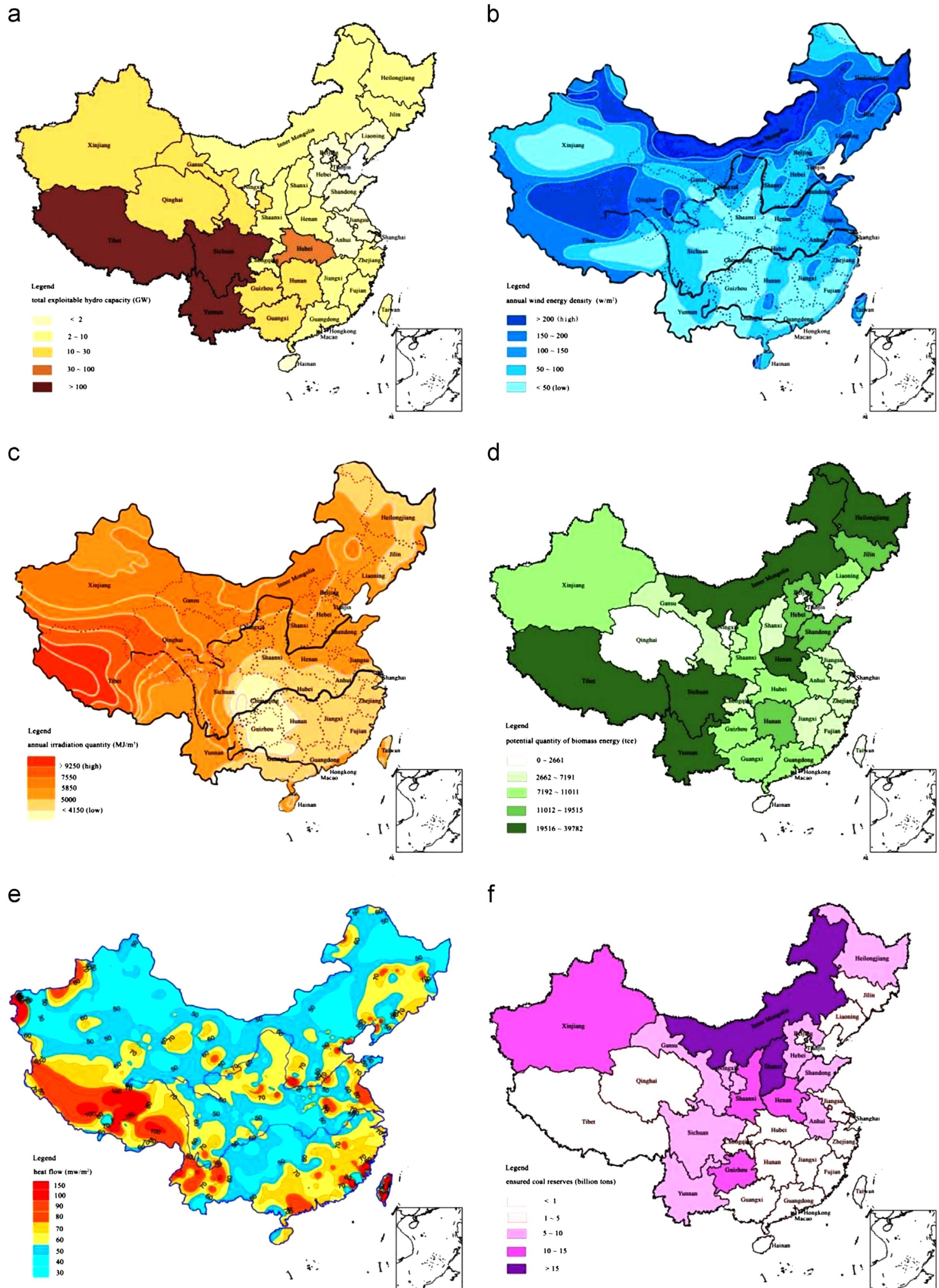

Fig. 1. Spatial distribution of major renewable energies and coal resources in China. (a) Hydropower. *Data source*: [32], (b) wind power. *Source*: [33,34], (c) solar energy. *Source*: [33,34], (d) biomass energy. *Data source*: [35], (e) geothermal power. *Source*: [34,36], (f) coal. *Data source*: [39].

technologies [10]. According to official statistics, the ensured coal reserves in China are 279.4 billion tons [39]. Coal resources are the most abundant in Shanxi and Inner Mongolia, where the ensured coal reserves are 84.4 and 77.0 billion tons, specifically. It is followed by Xinjiang, Shaanxi, Guizhou and Henan, where the ensured coal reserves are all from 10 billion tons to 15 billion tons. The least represented are those regions such as Shanghai, Xizang, Zhejiang, Hainan, Guangdong, Tianjin, Hubei, Beijing, Fujian, Jiangxi and Guangxi, where the ensured coal reserves are all smaller than 1 billion tons (see Fig. 1f).

3. Spatial distribution of energy consumption and its major influencing factors in China

In China, the major energy consumers are far away from energy-abundant areas, where the national energy production bases are located. To conduct the sustainable development of renewable energy, it is important to recognize the spatial distribution of energy consumption and its major influencing factors in China (see Fig. 2).

3.1. Electricity consumption

Electricity is an important sector of final energy consumption in China. Furthermore, during the direct use, processing and transformation of fossil fuels, i.e. coal, oil and natural gas, electricity is often needed. Therefore, the spatial distribution of electricity consumption can reflect that of energy consumption. According to official statistics, the electricity consumption in China in 2010 is 4193 billion kW h [39]. The electricity consumption is the largest in Guangdong, Jiangsu, Shandong, Zhejiang, Hebei and Henan, where the electricity consumption is larger than 200 billion kW h. It is followed by Liaoning, Sichuan and Inner Mongolia, where the electricity consumption is from 150 billion kW h to 200 billion kW h. The least represented are those regions such as Xizang, Hainan and Qinghai, where the electricity consumption is smaller than 50 billion kW h (see Fig. 2a).

3.2. Per capita GDP

The relationship between energy consumption and per capita GDP may be various in different countries and development stages [40]. However, it is recognized that more than 30 years of rapid economic growth has also burned China's substantial energy [41]. In general, in the eastern coastal provinces, due to comprehensive advantages, a mass of energy-consuming industries have been preferentially distributed since 1978. It makes the economy develop the fastest in China. Then the scale effect makes population and economy centralize in the eastern areas of China. Consequently, there exists bidirectional causality between energy consumption and per capita GDP in China [40]. As shown in Fig. 2a and b, where per capita GDP is large, such as in the eastern coastal provinces, the electricity consumption is generally large. However, in Guizhou, Yunnan, Gansu, Xizang, etc., per capita GDP and the electricity consumption are both small.

3.3. Population and economic density

Population and economic density are two important indicators to impact the spatial distribution of energy consumption. In general, where population and economic densities are large, the energy consumption is generally large. According to official statistics, the average population density in China in 2010 is 140 person/km^2, and the average economic density is 4.60 million yuan/km^2 [39]. The population density is almost consistent with economic density in spatial distribution (see Fig. 2c and d). Specifically, except for Shanghai, Beijing and Tianjin, population and economic densities in Jiangsu, Zhejiang, Guangdong, Shandong and Henan are the largest. It is followed by the neighboring provinces in the eastern and central areas of China. The least represented are those regions such as Xizang, Qinghai, Xinjiang, Inner Mongolia, and Gansu, etc., mainly distributed in the western areas of China.

3.4. Urbanization level

China has been recognized as one of the world's fastest developing countries, specifically for its rapid urbanization in the past decades [1]. Urban contributions make up 84% of China's commercial energy usage. The 35 largest cities in China, which contain 18% of the population, contribute 40% of China's energy uses and CO_2 emissions [42]. Therefore, urbanization level is also an important indicator to impact the spatial distribution of energy consumption. According to official statistics, the urbanization level in China in 2010 is 49.68% [39]. The urbanization levels in Shanghai, Beijing and Tianjin are the largest, which are all larger than 70%. The least represented are those regions such as Xizang, Guizhou, Yunnan, Gansu, and Henan, etc., mainly distributed in the western and central areas of China (see Fig. 2e).

3.5. Other factors

Population and economy are direct influencing factors for the spatial distribution of energy consumption. There are indirect influencing factors, such as natural and social conditions. For example, water is recognized as the most critical resource in China [43]. The spatial distribution of population and economy is largely dependent on water resources. According to official statistics, the utilization ratio of water resources, which is defined by the proportion of socio-economic water use to total volume of water resources, is close to 20% in China in 2010 [39]. The utilization ratios of water resources in Ningxia, Shanghai, Tianjin, Beijing, Jiangsu and Hebei are the largest, which are all larger than 100%. The utilization ratios of water resources in Shandong, Shanxi, Gansu, Xinjiang, Inner Mongolia and Henan are all larger than 40%, where the development of population and economy is restricted by scarce water resources (see Fig. 2f).

4. Positive and negative environmental impacts of major renewable energies in China

Renewable energies are all low-carbon energies and have less impact on environment compared with fossil energy from a global perspective. However, this kind of concept is often overstated or distorted in China so that the negative environmental impacts of renewable energies are ignored. In fact, all kinds of renewable energies are not zero-carbon energies. They may damage the local or regional environment in different ways. To promote the sustainable development of renewable energy, it is important to recognize both the positive and negative environmental impacts.

4.1. Environmental impacts of hydropower

Hydropower has an important potential to be marked as a green power. It offers ecological advantages from a global perspective, such as reduction of greenhouse gases (GHG, including CO_2, CH_4, N_2O, etc.) and flooding risk. However, the construction and operation of hydropower plants may have negative environmental impacts by changing environment and affecting land use, homes, and natural habitats in the dam areas, such as submergence of forestland and concomitant loss of bio-diversity, harm to

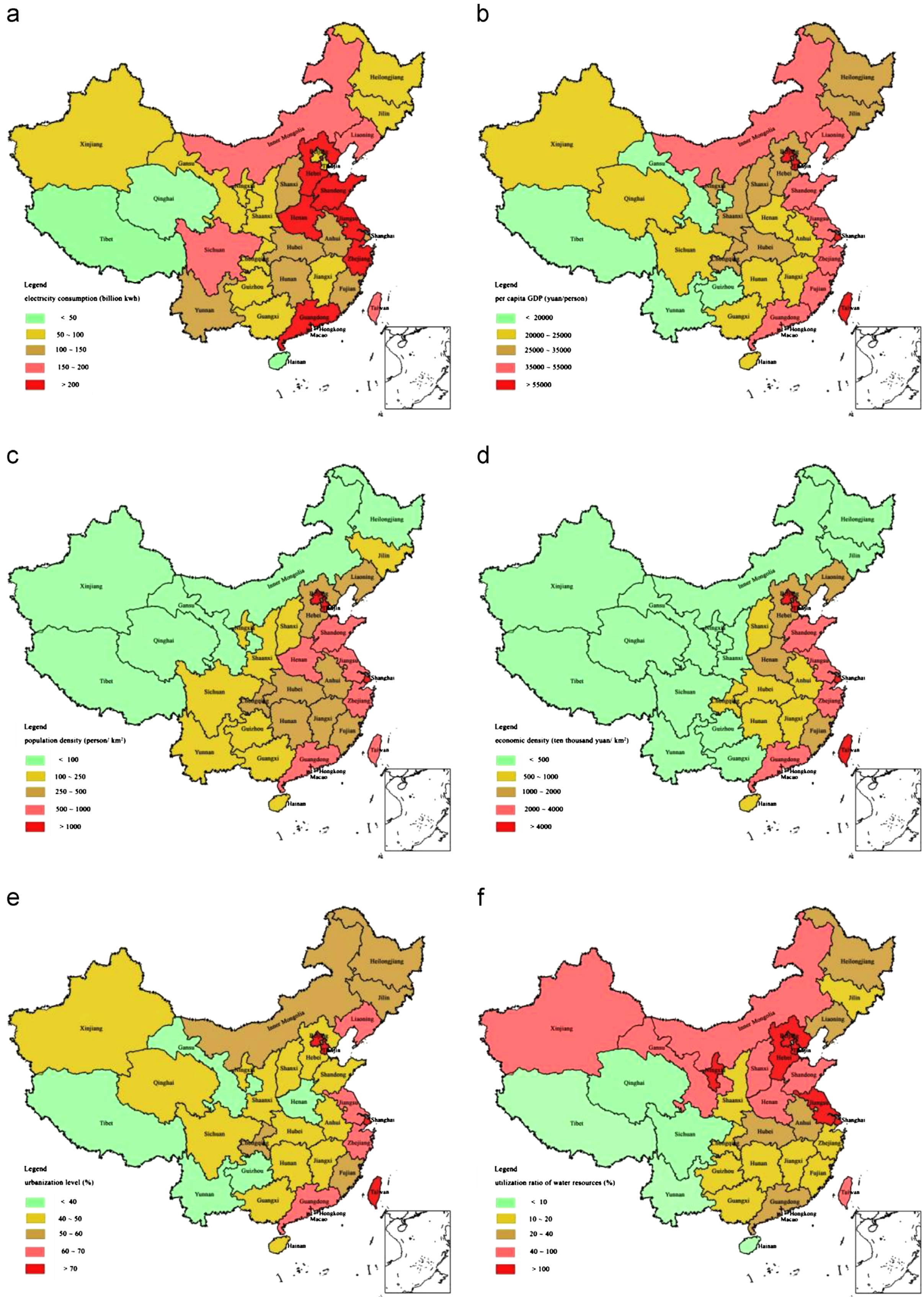

Fig. 2. Spatial distribution of energy consumption and its major influencing factors in China. (a) electricity consumption, (b) per capita GDP, (c) population density, (d) economic density, (e) urbanization level, (f) utilization ratio of water resources.
Data source: [39].

fish populations, a significant change in natural flow regimes, slopes destabilization and climatic alterations [44,45]. There are the environmentally aware, the socially sensitive and the politically involved conscious that readily identify hydroelectric shortcomings and advocate dam removal [46,47]. More importantly, though hydropower plants do not burn fossil fuels and directly produce GHG, some CO_2 is still produced during the manufacture and construction of the projects, e.g. when producing the concrete and steel used to build the dam, a lot of electricity which mainly comes from thermal power is consumed. Furthermore, hydroelectric dams may produce significant amounts of CO_2, CH_4 and N_2O, and in some cases produce more of these greenhouse gases than power plants running on fossil fuels [45]. This shows that both the positive and negative nature of hydropower must be carefully considered.

4.2. Environmental impacts of wind power

Wind energy is commonly recognized to be environmentally friendly, which means no fossil energy consumption, little environmental pollution, short construction cycle, flexible construction scale and good socio-economic benefits [48]. However, there are negative environmental impacts due to the installation and operation of the wind turbines that cannot be ignored [48,49]. The principal environmental impacts of wind energy have been noise, visual impacts, safety and impact on wildlife and natural habitats, global and local climate change, electromagnetic interference, energy costs of materials, landform disturbance, land requirements, waste water and solid waste. Some of these impacts may seem minor at present, but the potential long-term effects are not yet known. Some of these impacts seem great from some built wind farms in China. For example, the Qitaihe Wind Farm in Heilongjiang province is located in the mountain top because wind power resources are abundant there. Therefore, a winding road which is dozens of kilometers long and ten meters wide should be constructed so that the bulky wind power equipment can be transported. Then dozens of hectares of forests have been destroyed. Water loss and soil erosion have taken place more easily on the hill slopes. Moreover, the big noise produced by the wind farm has frightened away a lot of animals. On a separate note, though wind turbines do not directly pollute the atmosphere with GHG, some CO_2 is still produced during the manufacture of wind power equipment and the construction of wind farms.

4.3. Environmental impacts of solar energy

The reduction of greenhouse gases pollution is the main advantage of utilizing solar energy [50]. Furthermore, it has additional positive implications such as prevention of toxic gas emissions, reclamation of degraded land and improvement of water quality [51]. However, it also has to face potential negative environmental impacts such as visual intrusion, releases of chemicals and pollutant, impact on ecosystems, use of toxic and flammable materials [51]. For example, the energy spent for manufacture and installation of a PV power generation system can be recouped in about 1.5 years. However, it can last for about 25 years. It means that a PV power generation system can produce electricity without GHG emissions for more than 23 years [37]. Therefore, it can be concluded that solar energy systems offer significant protection to the environment. However, the PV power generation system in China is still at the infancy stage due to high cost of PV cells and solar electricity. China produces more than 50% of the world′s PV cells while the share of domestic market is less than 1% of the world [37]. It is well known that the produce of PV cells requires high consumption of energy and has a lot of contamination, such as poisonous and harmful gases, acidic and alkaline waste water, and heavy metal waste residue. That′s to say, China has made great contributions to the carbon reduction of the world at the cost of its own environmental pollution by exporting a lot of PV cells to the developed countries.

4.4. Environmental impacts of biomass energy

Biomass energy is recognized to be carbon neutral because the plants take up CO_2 from the air while they are growing and then return it to the air when they are burned, thereby causing no net increase. It can help mitigate climate change, reduce acid rain, soil erosion, water pollution and pressure on landfills, provide wildlife habitat, and help maintain forest health through better management [52]. However, negative environmental impacts of biomass energy systems may be obtained when the amount of CO_2 removed from the atmosphere by the photosynthesis of biomass is less than the amount produced during an incomplete combustion and inefficient energy production. Moreover, biomass isn′t nutrient neutral [52]. Improper management of biomass energy could create serious environmental problems such as emission of harmful gases, depletion of nutrients, topsoil erosion, soil salinization and water pollution due to fertilizer and pesticide runoff. For example, the Chinese central and local governments have been popularizing the biogas digesters by a series of preferential policies. However, some of the biogas digesters have gone out of use soon after construction due to technological nonattainment or improper management [37]. The residues of abandoned biogas digesters may have great impact on local environment, such as land encroachment, water pollution and solid contaminant.

4.5. Environmental impacts of other renewable energies

Few studies have looked into the environmental impacts of geothermal and ocean energies in China as they have not been large-scale exploited. The distributed applications of geothermal and ocean energies have less impact on the environment than other major renewable energies. However, as geothermal and ocean energies offer many advantages over fossil fuels [53,54], large-scale geothermal power plants and tidal power stations may develop fast in the future. Therefore, the negative environmental impacts need to be taken care. Specifically, the negative environmental impacts of geothermal energy may be disposal of wastewater, reinjection, removal of boron, CO_2 emission and landscape erosion [53]. The negative environmental impacts of ocean energy may be alteration of currents and waves, alteration of substrates and sediment transport and deposition, alteration of habitats for benthic organisms, noise during construction and operation, emission of electromagnetic fields, interference with animal movements and migrations, and strike by rotor blades or other moving parts [55].

5. Dominant recommendations from a geographical and environmental perspective

Based on the spatial disparity and consistency of major renewable energies, coal resources, energy consumption and its major influencing factors (see Figs. 1 and 2), and the positive and negative environmental impacts of major renewable energies, the dominant recommendations for the sustainable development of renewable energy in China are suggested as follows.

5.1. Construct the national energy production bases according to the resource distribution

According to a series of China′s energy development plans and the spatial distribution of major renewable energies and coal resources in China, some national energy production bases at large scale should be immediately constructed to cope with the energy crisis and global climate change.

5.1.1. Construct fourteen national coal bases

As China′s coal-based energy structure does not change in the medium- and long-term, 14 national coal bases should be well constructed under the guidance of their specific plans [56], i.e. Shendong (across Inner Mongolia and Shaanxi), Shanbei (in the north of Shaanxi), Huanglong (across Shaanxi and Gansu), Jinbei (in the north of Shanxi), Jinzhong (in the central of Shanxi), Jindong (in the east of Shanxi), Mengdong (in the east of Inner Mongolia and northeast of China), Lianghuai (in the north of Anhui), Luxi (in the west of Shandong), Henan (in Henan), Jizhong (in the central of Hebei), Yungui (across Yunnan and Guizhou), Ningdong (in the east of Ningxia) and Xinjiang (in Xinjiang), which are all located in coal-abundant provinces (see Fig. 1f).

5.1.2. Construct thirteen national hydropower bases

Emphasis should be highlighted on the planning and development of 13 national hydropower bases [32,57], i.e. Jinshajiang River (across Sichuan and Yunnan), Yalongjiang River (in the west of Sichuan), Daduhe River (in the central and west of Sichuan), Wujiang River (across Guizhou and Chongqing), the upper main stream of Yangtse River (across Chongqing and Hubei), Nanpanjiang and Hongshui River (across Guizhou and Guangxi), Lancangjiang River (across Tibet and Yunnan), the upper main stream of Yellow River (across Qinghai, Gansu and Ningxia), the middle main stream of Yellow River (across Inner Mongolia, Shaanxi and Shanxi), Xiangxi (in the west of Hunan), Min-Zhe-Gan (across Fujian, Zhejiang and Jiangxi), Dongbei (across Heilongjiang, jilin and Liaoning), Nujiang River (across Tibet and Yunnan), which are all located in hydropower-abundant provinces (see Fig. 1a).

5.1.3. Construct ten national wind power bases

Ten national wind power bases, i.e. Jiuquan in Gansu, Hami in Xinjiang, Heibei, Jilin, east and west of Inner Mongolia, coastal areas of Jiangsu and Shandong, Heilongjiang and Shanxi [57,58], which are all located in wind power-abundant provinces (see Fig. 1b), should be well planned and constructed. The installed capacity of each wind power base will reach more than 10 GW after its completion. The main task of these wind power bases is to resolve the problems on large-scale wind power integration on power system. Moreover, the feasibility should be actively explored so that non-grid-connected wind power can be directly and locally used in high-energy-consuming industries at large scale [59].

5.1.4. Construct some demonstration projects of other renewable energies

Some demonstration projects of large PV power stations (potentially in Qinghai, Ningxia, Gansu, Tibet, Inner Mongolia, etc., where solar energy resources are the most abundant, see Fig. 1c), biomass power plants (potentially in Sichuan, Yunnan, Tibet, Heilongjiang, Inner Mongolia, etc., where biomass energy resources are the most abundant, see Fig. 1d), geothermal power plants (potentially in Tibet, Yunnan, Zhejiang, Fujian, Guangdong, etc., where geothermal power resources are the most abundant, see Fig. 1e) and tidal power stations (potentially in Zhejiang, Guangdong, Fujian, Shandong, Liaoning, etc., where ocean energy resources are the most abundant) should be initiated and promoted though their installed capacities are hard to reach the level of the above national energy production bases. Besides, the distributed application systems of solar energy, biomass energy, geothermal power and ocean energy should be advocated more strongly.

5.2. Integrate different energies on the basis of their natural features and spatial consistency

According to the diurnal or seasonal variation of runoff, wind speed, solar radiation, tidal energy, etc. and the spatial consistency of major renewable energies and coal resources in China, all kinds of energies can complement each other when two or more are integrated together (see Fig. 3). Among those integrations, the following patterns should be popularized for China.

5.2.1. Integration between stable and unstable electric sources

Stable and unstable electric source can be cooperated with each other to enhance the stability and efficiency of the whole power system. Stable electric sources, such as thermal power, biomass energy and geothermal power, can relieve the hydropower system during dry seasons and receive its support during flood seasons. They can also relieve the wind power (solar energy or ocean energy) system when wind speed (solar radiation or tidal energy) is low and receive its support when it is high. This kind of pattern tends to be applied in the areas where the unstable electric source is abundant because coal and biomass energy are easier to be transported. It will be better if stable electric source is also rich there. Specifically, as the coal resources, wind power and solar energy are all abundant in the west and north of China (i.e. Inner Mongolia, Xinjiang, Gansu, Shanxi, Shaanxi, Henan, etc., see Fig. 1f, b and c), the integration between thermal power and wind power (or solar energy) can be vigorously advocated.

5.2.2. Integration among unstable electric sources

Integration among unstable electric sources (i.e. wind power, solar energy, ocean energy and hydropower) should be promoted on the basis of the natural features and spatial consistency. For example, the wind power system can relieve the solar energy system in dark or rainy days, and receive its support in daylight or sunny days. As wind power and solar energy are both abundant in Inner Mongolia, Xinjiang, Gansu, Shanxi, Hebei, Shandong, etc. (see Fig. 1b and c), the wind-solar system can be popularized in these provinces.

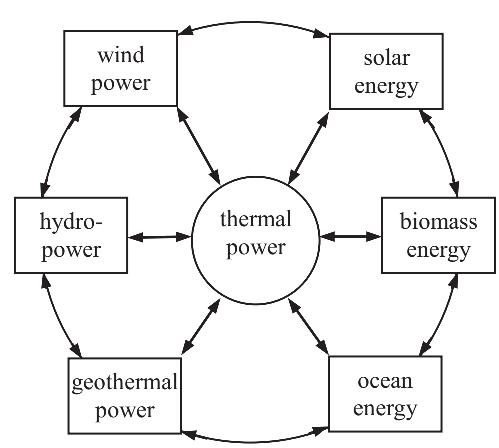

Fig. 3. Integration of different energies.

5.2.3. Integration among stable electric sources

Integration among stable electric sources (i.e. thermal power, biomass energy and geothermal power) should be also promoted. As the thermal power system provides a dominant electric source and biomass energy is largely used in China, co-firing of coal and biomass (i.e. biomass is burned in combination with coal in boilers at power plants) should be highlighted. Inner Mongolia, Heilongjiang, Henan, Shandong, etc., where biomass energy and coal resources are both abundant (see Fig. 1d and f), are the key regions to popularize this kind of pattern to reduce GHG emissions (including CO_2, CH_4, N_2O, etc.).

5.3. Adjust the overall layout of socio-economic development consistent with renewable energies

As national energy production bases are mainly located in the west and north of China while population and economy are both centralized in the east and south (see Figs. 1 and 2), and renewable energy development may alleviate the conflict between energy supply and demand to some extent in some areas, the spatial distribution of some important socio-economic sectors should be adjusted in an integrated perspective.

5.3.1. Optimize the spatial distribution of China's population and industries

China should conform to the basic rule of socio-economic development and promote a healthy urbanization and industrialization, i.e. ensure a proper and orderly development of population and economy in cities and towns, especially in urban agglomerations which have advantageous natural conditions, solid economic bases and opening market environment, so that all kinds of resources (i.e. water, land and energy) can be used high efficiently and rationally. Generally speaking, urban agglomerations in the east and south of China, where population and economic densities are the largest (see Fig. 2c and d), are the key areas to admit more population and industries, i.e. the Yangtze River Delta (across Shanghai, Jiangsu and Zhejiang), the Pearl River Delta (in Guangdong), Beijing-Tianjin-Tanggu (across Beijing, Tianjin and Hebei), Shandong Peninsula (in Shandong) urban agglomerations, etc. However, urban agglomerations in the west and north of China, such as Chengyu (across Sichuan and Chongqing), Guanzhong (in Shaanxi), Jinzhong (in Shanxi), northern slope of Tianshan Mountains (in Xinjiang), Hu-Bao-E (in Inner Mongolia), Lan-Bai-Xi (across Gansu and Qinghai) and so on, should also be highlighted with the large-scale development of renewable energies. Moreover, with the industrial upgrading of the east and south of China, some high-energy-consuming industries should be transferred to the west and north of China. However, some high-energy and water-consuming industries had better be transferred to the eastern coastal areas due to the large-scale development of wind power (see Fig. 1b) and water scarcity in the north of China (see Fig. 2f).

5.3.2. Optimize the spatial distribution of China's power grids

Due to the spatial disparity of energy supply and demand (see Figs. 1 and 2) and the instability of power generation system for renewable energies, China should construct a more powerful electricity grid system. Specifically, China has initiated the west-to-east electricity transmission project since the middle 1990s and increased the scale significantly since the early 2000s. This great project utilizes power grids to transfer the hydropower or thermal power generated in resource-rich areas (i.e. Guizhou, Yunnan, Guangxi, Sichuan, Inner Mongolia, Shanxi, Shaanxi, etc., see Fig. 1a and f) to economy-developed and high-energy-consuming areas (i.e. Guangdong, Shanghai, Jiangsu, Zhejiang, Beijing, Tianjin, Hebei, etc., see Fig. 1a–e). With the large-scale development of new national coal bases (i.e. Xinjiang, Mengdong, etc.), hydropower bases (i.e. Jinshajiang, Lancangjiang, Nujiang River, etc.) and wind power bases (i.e. Gansu, Xinjiang, Inner Mongolia, etc.), the west-to-east electricity transmission project should continue to be enlarged in the future. Similar electricity transmission projects should be constructed for the sustainable development of renewable energies in some local areas. For example, as many local power grids are simply too small to carry all the wind power being generated and the cost of energy storage is very high, about 30% of China's total installed capacity cannot get access to the power grids, and about 10% of China's total wind power generation is curtailed in 2010 [60]. Therefore, China needs to significantly improve its power grids and coordinate the renewable energy development with the construction of power grids.

5.3.3. Optimize the spatial distribution of other kinds of energy transportation networks

Other kinds of energy transportation networks, such as the north-to-south coal transmission project, the west-to-east coal transmission project, the west-to-east gas transmission project, and similar coal and gas transmission projects in local areas, should also be highlighted to promote the sustainable development of renewable energies. Specifically, the north-to-south and west-to-east coal transmission projects transfer coal in resource-rich areas (i.e. Shanxi, Shaaxi, Inner Mongolia, etc., see Fig. 1f) to economy-developed and high-energy-consuming areas (i.e. Shanghai, Jiangsu, Zhejiang, Fujian, Guangdong, Tianjin, Hebei, etc., see Fig. 1a–e) mainly by railway and sea. The west-to-east gas transmission project utilizes pipelines to transfer gas from the western provinces (i.e. Xinjiang, Gansu, Ningxia, etc.) to the eastern provinces (i.e. Jiangsu, Shanghai, Guangdong, etc.). With the support from the transferred coals and gases, the eastern provinces have more coals to generate electricity and less demands from the west-to-east electricity transmission project. It helps to alleviate the impact of the renewable energy development on the power grids. Considering the rapid development of renewable energies, this kind of coal and gas transportation networks, including railways, highways, pipelines, sea and river transportation, should continue to be perfected in the future China.

5.4. Promote a moderate renewable energy development to maximize the environmental benefits

The renewable energy development is facing both opportunities and challenges in China. It has both positive and negative environmental impacts as mentioned in Section 4. If the renewable energy development proceeds too slowly, the fossil energy crisis may become more serious and the goal for emissions reduction may not be achieved. If the renewable energy development proceeds too fast, many technical, economic and environmental obstacles may not be cleared away in a short time. Therefore, a moderate renewable energy development should be stressed.

5.4.1. Control the development speed of renewable energies through rational planning

Rapid development of renewable energies has happened in recent years in China. The main reasons are complex, e.g. the Chinese central government has formulated a series of encouraging policies to cope with the energy crisis and global climate change, some large power companies try to seize the limited market share, some local governments hope to attract huge investments as their political achievements, etc. The explosions of wind power and PV industry have brought some serious problems [37], e.g. the development of wind power is much faster

than the construction of power grids, some wind farms have low economic benefits due to construction in haste, wind power accidents occur frequently because of immature technology and imperfect management, and the PV industry consumes a lot of electricity and causes serious environmental pollution in local areas. Therefore, a unified development planning of all kinds of renewable energies should be formulated by the Chinese central and local governments. It is important to point out that, due to various geographical features of major renewable energies, coal resources, energy consumption and its major influencing factors (see Figs. 1 and 2) and different technical, economic and environmental feasibilities, each province in China should set a proper goal for the development speed of each kind of renewable energies in the national and regional planning.

5.4.2. Establish and perfect a quota system for renewable energy development across provinces

The quota system aims to support a sustainable development of renewable energies. Under the quota system, power companies should receive a certain amount or proportion of their electricity generation to come from renewable energies. Grid companies should buy a certain percentage of electric power from renewable energies. In fact, China′s concept for the quota system has been put forward in several projects and regulations previously, e.g. the proportion of renewable energy consumption to total energy consumption was set as 10% in 2010 and 15% in 2020 in China′s medium- and long-term development plan for renewable energy which was released in 2007 [61]. Some provisional regulations stipulate that the installed capacity of renewable energies of large state-owned power companies should reach 5–10% of their installed capacity of thermal power. Therefore, the large state-owned power companies accelerate the renewable energy development so that they can develop more thermal power plants and obtain more profits. However, some grid companies refuse to accept the electric power generated from renewable energies because of its instability. Therefore, a well-organized quota system will benefit and normalize China′s renewable energy development. Specifically, due to the spatial disparity of energy supply and demand in China (see Figs. 1 and 2), a quota system for renewable energy development across provinces should be established and perfected, i.e. as for electric power producers and users, each province in China should be given a proper quota to produce and consume electric power generated from renewable energies.

5.4.3. Strengthen the environmental impact assessment system for renewable energy development

China′s renewable energy development is advocated by policy makers because renewable energies are considered as low-carbon and clean energies. Moreover, the renewable energy development can bring huge investments to local governments and stimulate the economic growth. For example, the ocean energy power investment is 40,000–50,000 RMB/kW, the offshore wind power investment is about 15,000 RMB/kW, the solar PV power investment is 10,000–15,000 RMB/kW, the investments for onshore wind power, biomass power and geothermal power are all about 8000 RMB/kW, and the hydro power investment is about 6000 RMB/kW. They are all higher than the thermal power investment which is about 4000–5000 RMB/kW. Besides, to produce 1000 t of polysilicons, which are raw materials to manufacture PV cells, it needs about one billion RMB of investment. Under such great allures, some local governments often create some favorable conditions to support the renewable energy development, and the environmental protection departments which are directed by the local governments often relax the requirements of the environmental impact assessment. However, as mentioned in Section 4, the renewable energy development is clearly associated with an array of both positive and negative environmental impacts. Therefore, the environmental impact assessment system in China should be strengthened when renewable energy development projects are planned. Socio-economic and environmental impacts of renewable energy development projects need to be assessed in line with national and international guidelines. The negative environmental impacts should be fully estimated and analyzed so that such impacts can be reduced to minimum.

6. Conclusions

China′s renewable energy development has become a key to the sustainable development of socio-economic system in rapid urbanization and industrialization. It should be promoted unswervingly. However, China also faces many challenges to achieve the sustainable development of renewable energy itself. Besides some technical, economic and policy issues, an integrated spatial coordination and a scientific environmental cognition are two important factors for it. The spatial coordinated development should be implemented according to the spatial disparity and consistency among the major renewable energies, coal resources, energy consumption and its major influencing factors in China. The positive and negative environmental impacts of major renewable energies in China should be both carefully considered. Specifically, the negative environmental impacts should be highlighted to avoid pell-mell development. Suggestions and recommendations need to direct China′s renewable energy development from a geographical and environmental perspective.

First, China should construct the national energy production bases according to the resource distribution, including 14 national coal bases, 13 national hydropower bases, 10 national wind power bases, and some demonstration projects of other renewable energies. Second, stable and unstable electric sources should be integrated on the basis of their natural features and spatial consistency. Third, the overall layout of socio-economic development (i.e. population, industries, power grids and other kinds of energy transportation networks) in China should be adjusted to be consistent with the new development of renewable energies. Finally, China should promote a moderate renewable energy development to maximize the environmental benefits.

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